Pageoph, Vol. 117 (1979), Birkhäuser Verlag, Basel

On Chinese Earthquake History – An Attempt to Model an Incomplete Data Set by Point Process Analysis

By W. H. K. LEE[1]) and D. R. BRILLINGER[2])

Abstract – Since the 1950s, the Academia Sinica in Peking, People's Republic of China, has carried out extensive research on the Chinese earthquake history. With a historical record dating back some 3000 years, a wealth of information on Chinese earthquakes exists. Despite this monumental undertaking by the Academia Sinica, much work is still necessary to correct the existing earthquake data for historical changes in population, customs, modes of communication, and dynasties. In this paper we report on the status of our investigation of Chinese earthquake history and present some preliminary results. By applying point process analysis of earthquakes in 'Central China', we found suggestions of (1) lower earthquake activity at intervals of about 175 years and 375 years, and (2) higher earthquake activity at an interval of about 300 years.

Key words: Earthquake recurrence; Seismicity patterns; Tectonics of China.

Introduction

Although seismicity is one of the primary data sources in making long-term earthquake prediction and hazard evaluations, knowledge of seismicity is rather limited. Modern seismographs began operation at the end of the 19th century, and adequate instrumental records for locating earthquakes on a worldwide basis date back only to 1904 for events of about magnitude $6\frac{1}{2}$ and greater. Indeed, accurate location of earthquakes (magnitude equal to or greater than 5) around the world became possible only after the establishment of the World-Wide Standardized Seismograph Network in 1963. Even in a well-studied area such as California, regional seismic networks were established in the 1930s and local networks in the 1960s. Consequently, knowledge of instrumentally determined seismicity covers only a short period of several decades.

In the framework of plate tectonics, tens or hundreds of years may be required to accumulate sufficient strains to generate large earthquakes. To identify seismic gaps and to determine how often a large earthquake occurs, accurate seismicity data covering periods of hundreds or thousands of years are required. Except for extremely active seismic regions, the instrumentally determined seismicity covers too short a

[1]) Office of Earthquake Studies, US Geological Survey, Menlo Park, CA, USA.
[2]) Department of Statistics, University of California, Berkeley, CA, USA.

period, and we must therefore rely upon historical records to estimate long-term seismicity.

With the exception of the Middle East, only China has a continuously recorded history extending back some 3000 years. In this paper we report on the status of our investigation on Chinese earthquakes, and present some preliminary results. We will also discuss a variety of difficulties which we encountered in the course of our study.

Source materials on Chinese Earthquakes

The first reliable description of a Chinese earthquake (in the 12th century B.C.) appeared in Lushi Chunqiu (Annals of Mr. Lu) compiled in the 3rd century B.C. Several earthquakes were mentioned in Shiji (Records of the Grand Historian) written by Si-ma Qian in the 1st century B.C. The first Chinese earthquake catalog appeared as a subsection of natural omens in Hanshu (Standard History of the Former Han Dynasty) by Ban Gu in the 1st century A.D. A list of 13 earthquakes, including damage and casualties, were summarized. In all of the subsequent 24 standard histories or dynasty records, earthquakes were reported.

In addition to normal reportings of earthquakes in the dynasty records, catalogs of Chinese earthquakes in various details also appear in numerous encyclopaedias and collected works. For example, earthquakes were summarized in a section of Tongzhi (Comprehensive Encyclopaedia of Institutions) by Zheng Qiao in A.D. 1149, and of Wenxian Tongkao (Critical Examination of Documents and Studies) by Ma Duan-lin in A.D. 1224.

With the advent of printing in the 10th century A.D., it became popular in China to compile local gazetteers describing details of local history and geography, especially in the Ming and Ching dynasties (14th–20th centuries). About 7500 local gazetteers, with a total of 110 000 chapters, are now in existence. Detailed descriptions of earthquakes were often found in these voluminous documents.

At the turn of the last century, many western seismologists were fascinated by the rich historical accounts of Chinese earthquakes. Several catalogs of Chinese earthquakes were published in the west, and these activities were reviewed by DRAKE (1912). All of these catalogs suffer two main defects in that references to the original sources are not specific, and that the epicenter and size of earthquakes are not adequately quantified.

In the 1950s, the Seismological Committee of the Academia Sinica initiated a systematic study of Chinese historical earthquakes in order to provide data on earthquake hazards in support of industrialization planning in China. The first task the Committee did was to compile, as completely as possible, all descriptions of earthquakes in Chinese literature and documents. In 1956, two large volumes totaling 1653 pages were published under the title of 'Chronological Tables of Earthquake Data of China' (ACADEMIA SINICA, 1956), and covered the period from 1189 B.C. to A.D. 1955.

Descriptions of earthquakes were extracted from over 8000 documents (many of them multi-volume publications) and were arranged by provinces. Within each province, entries were arranged in chronological order. Source references were cited, and notes were added to clarify ancient geographic names and errors in reporting. A summary of earthquake activity for each province was given, and an index by county and city of felt earthquakes was also included.

Attempts to quantify the historical descriptions of earthquakes were also carried out by the Academia Sinica. The results were published under the title 'Catalog of Chinese Earthquakes' (ACADEMIA SINICA, 1970a), and covered the period from 1177 B.C. to A.D. 1949. In this volume, the date, epicenter, magnitude, and epicentral intensity were provided for selected earthquakes noted in the 1956 compilation. Selections were based on whether or not sufficient information existed to deduce an earthquake location and magnitude. A brief summary of large earthquakes in China with magnitudes greater than or equal to 6 was also published (ACADEMIA SINICA, 1970b) and revised later (ACADEMIA SINICA, 1974, 1976). It covered the period from 780 B.C. to the present.

LEE, WU, and JACOBSEN (1976) presented a catalog of historical earthquakes in China from 1177 B.C to A.D. 1899 in a form suitable for computers. Their source materials are publications in Chinese of the Institute of Geophysics, Academia Sinica as described in the previous paragraph. A similar catalog for instrumentally determined earthquakes in China after A.D. 1900 (magnitude ≥ 6) was compiled by LEE, WU, and WANG (1978) from an extensive search of literature in Chinese, Japanese, and western languages.

Limitations of Chinese earthquake history

The accuracy and completeness of the Chinese historical earthquake data are difficult to evaluate. The questions are: How accurately and completely were the data recorded, passed down through history, and interpreted in the publications by Academia Sinica? Although fairly complete dynasty records began at about 200 B.C., printing did not begin in China until about A.D. 1000 so that very few original documents (written before A.D. 1000) exist and many ancient records are lost. However, the dynasty records and some ancient literature that survive are fairly well preserved through hand copying. Recent editions of dynasty records and ancient literature indicate only minor discrepancies among different earlier and independent versions, and small parts may be missing but could be filled in from other sources that quoted the missing text. The accuracy of Chinese dynasty records may be subject to debate. Earthquakes, like other disasters or unusual phenomena such as eclipses, were often regarded as punishments to the emperor and/or the people for their sins. As a result, the record of their occurrence could have been misrepresented by court historians.

Another consideration is that ancient China does not cover as much territory as modern China. Earthquakes would be recorded mostly within the territory that was under the control of the dynasty, and could have been noticed only if there was a sufficient number of people living near the epicentral region. Consequently, one would expect fewer and fewer earthquake reports as one goes back in time. In addition, many historical earthquakes (especially ancient ones) could not be interpreted and quantified because their descriptions are vague. There is also a tendency for the magnitudes of the older earthquakes to be underestimated because they are based on estimates of epicentral intensity and extent of damaged and felt areas. Because older documents tend to get lost and ancient population size was smaller than current, one would underestimate these parameters. The intensity scale was not described in ACADEMIA SINICA (1970a,b, 1974, 1976), but we suspect that the intensity scale used is that of HSIEH (1957) which consists of 12 degrees similar to the modified Mercalli scale. The magnitude (M) was determined by the formula

$$M = 0.58I_0 + 1.5$$

where I_0 is the epicentral intensity, and adjusted according to the extent of damaged and felt areas (LEE, 1958; ACADEMIA SINICA, 1970a). However, the method of adjustment is not described in the above-mentioned sources.

Historical and instrumentally determined seismicity

The historical earthquakes (before A.D. 1900) compiled from recent Chinese publications by LEE, WU, and JACOBSEN (1976) were plotted on a fault-map base as shown in Fig. 1. In Fig. 2, we show the instrumentally determined earthquakes (after A.D. 1900) compiled from various publications by LEE, WU, and WANG (1978). Comparison of these two figures indicates that there is a pronounced difference in the distribution of earthquakes – the apparent seismic quiescence of western China in the pre-instrumental period. This must be due virtually to the lack of historical data there because western China has a very low population and was not under the firm control of China until very recently.

To put the historical seismicity in proper perspective, one must consider the population distribution in time and space. Population distribution is in turn influenced by topography of the land. Figure 3 shows the general topography of China indicating that most of western China has an elevation in excess of 1000 meters. The modern population distribution is shown in Fig. 4. It is clear that most of the Chinese population is concentrated in land below 1000 meters. The boundaries of the past Chinese dynasties vary greatly as shown in Fig. 5 for a few examples. With these factors in mind, we may select a region of China that appears approximately homogeneous spatially in earthquake reportings. This area is taken to be from 30°N to 42°N, and from 100°E to 125°E as shown in Fig. 6. We call this study area 'Central China' (recognizing that it is not geographically the central region).

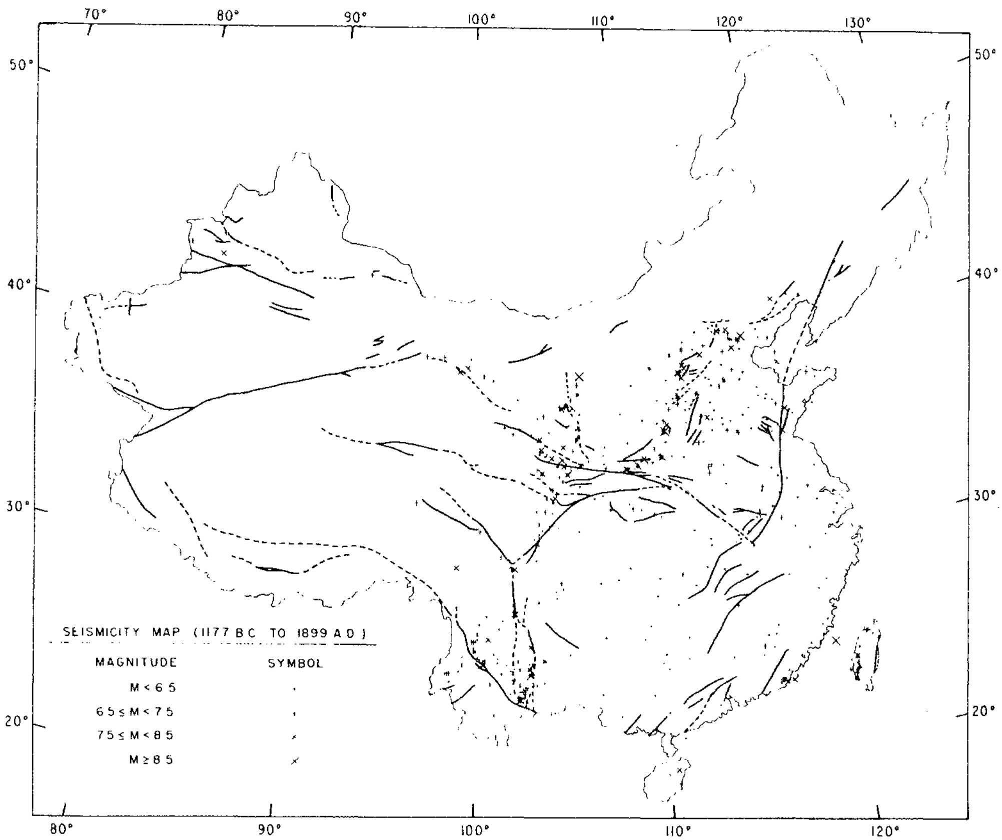

Figure 1
Map showing epicenter distribution of historical earthquakes in China (1177 B.C to A.D. 1899). Figure taken from LEE, WU, and JACOBSEN (1976, Fig. 3).

As discussed in the previous section, the magnitudes of historical Chinese earthquakes are probably underestimated. Although the historical catalog includes earthquakes of magnitude less than 6, we think that most of the events are probably of magnitude 6 or greater. Therefore we consider these historical earthquakes together with the instrumentally determined ones of magnitude 6 or greater.

In Table 1, we list the number of Chinese earthquakes by time and region. The reason for choosing the 'Central China' region becomes obvious. From 1177 B.C. to 0 B.C., there were 12 events in the Chinese catalogs, 11 of which occurred in 'Central China'. For the next thousand years, 'Central China' accounted for 90% of all Chinese earthquakes. From A.D. 1001 to A.D. 1900 only 55% of all Chinese earthquakes occurred in 'Central China'. During the instrumental period from 1901 to 1976, only 11% of all Chinese earthquakes occurred in 'Central China'.

If we assume that the instrumentally determined earthquakes are complete and that the recent seismicity is representative of the ancient one, then we must conclude

Table 1

Number of Chinese earthquakes by time and region

Time	Time period (years)	Number of earthquakes in China	Number of earthquakes in 'Central China'
1177 B.C. to 0 B.C.	1177	12	11
A.D. 1 to A.D. 1000	1000	42	38
A.D. 1001 to A.D. 1900	900	512	284
A.D. 1901 to A.D. 1976	76	579	65

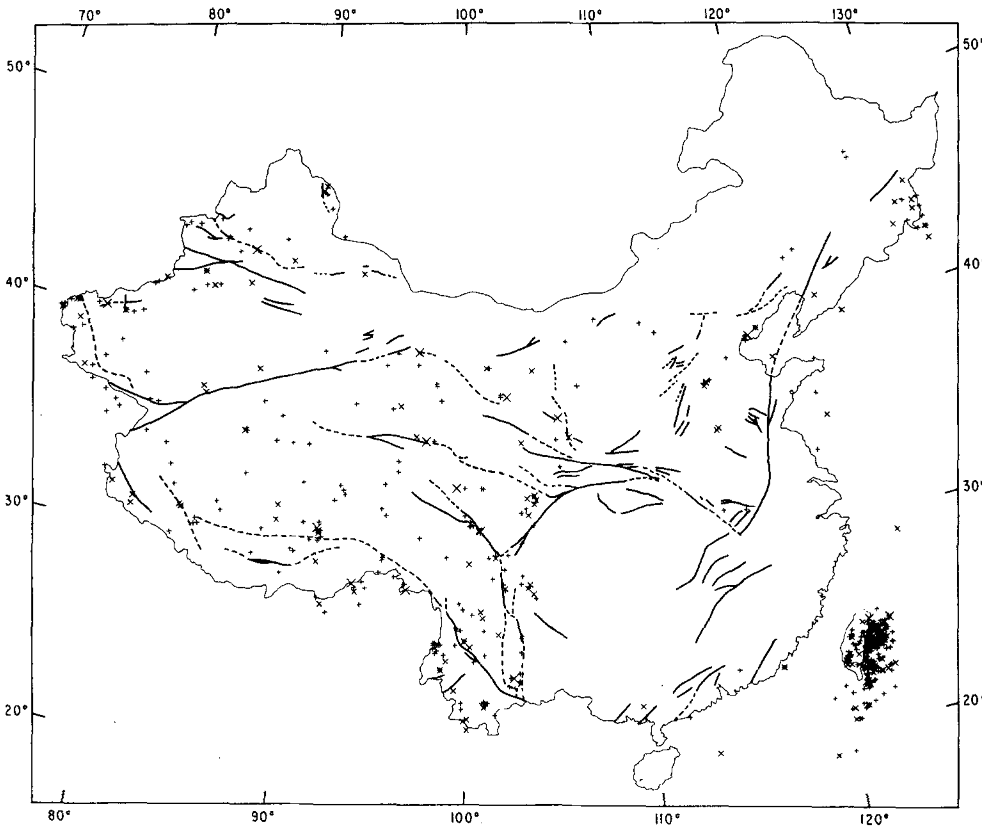

Figure 2

Map showing epicenter distribution of instrumentally determined earthquakes in China (A.D. 1901 to A.D. 1976). Figure taken from LEE, WU, and WANG (1978, Fig. 2).

that about two-thirds of all earthquakes in 'Central China' which would have occurred did not appear in the catalog for the period from A.D. 1001 to A.D. 1900. As noted in the previous section, printing and local gazetteers began in the 10th century but did not become widespread until the 15th century. If we take this into account, we have 231

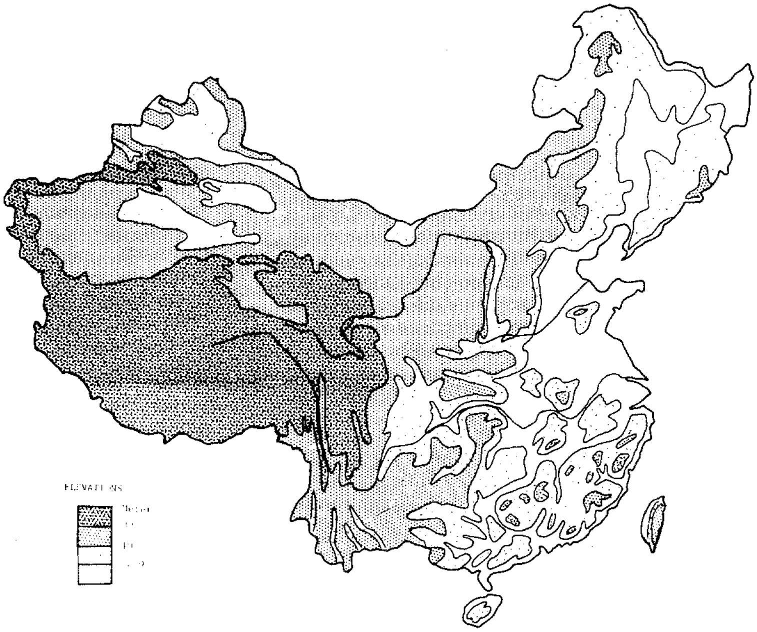

Figure 3
Generalized topography of China.

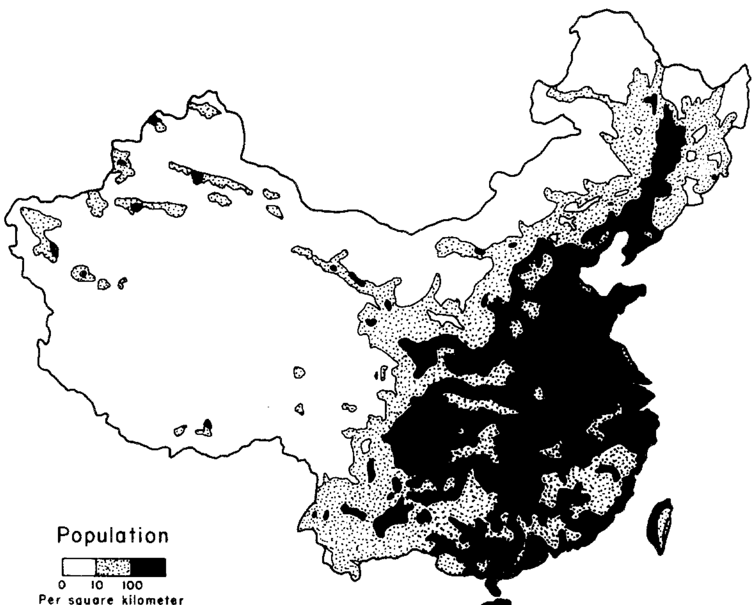

Figure 4
Population density map of modern China.

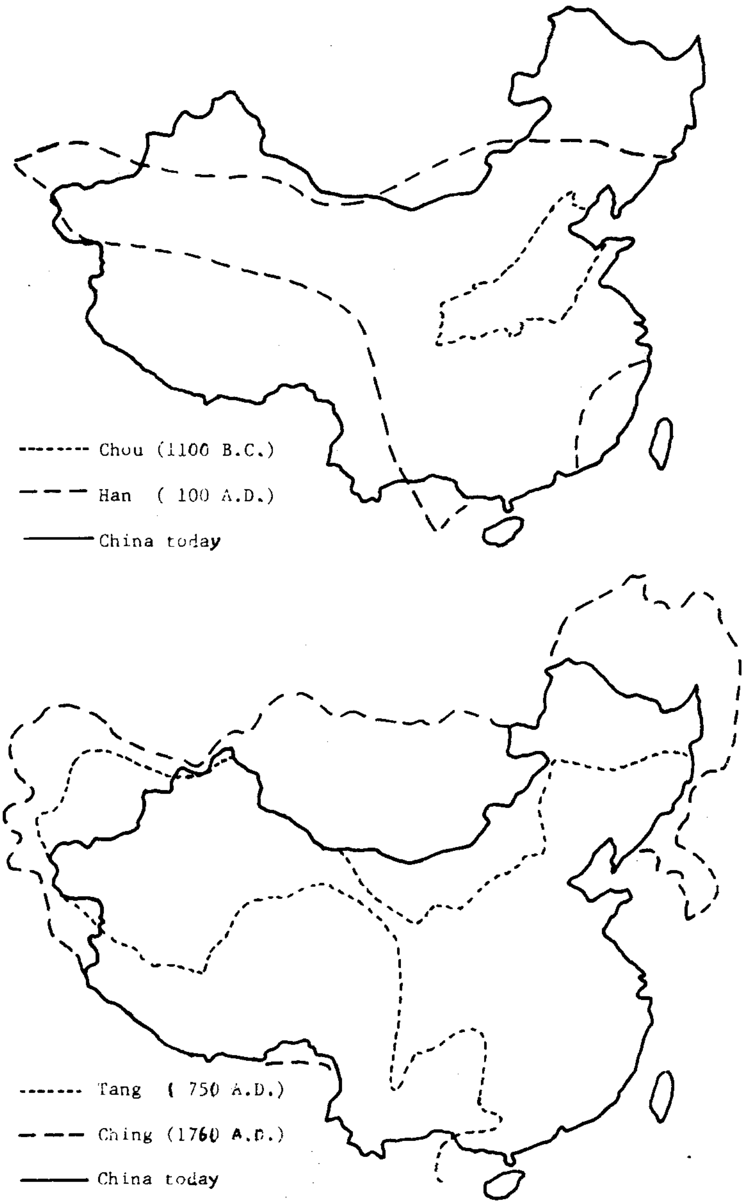

Figure 5
Approximate boundaries of Chou, Han, Tang, and Ching dynasties. Modified from FESSLER (1963).

earthquakes in 'Central China' from A.D. 1501 to A.D. 1900, yielding a rate of 58 earthquakes/century (versus the modern rate of about 86 earthquakes/century as shown in Table 3 later).

The above analysis clearly suggests that the present earthquake catalog is not

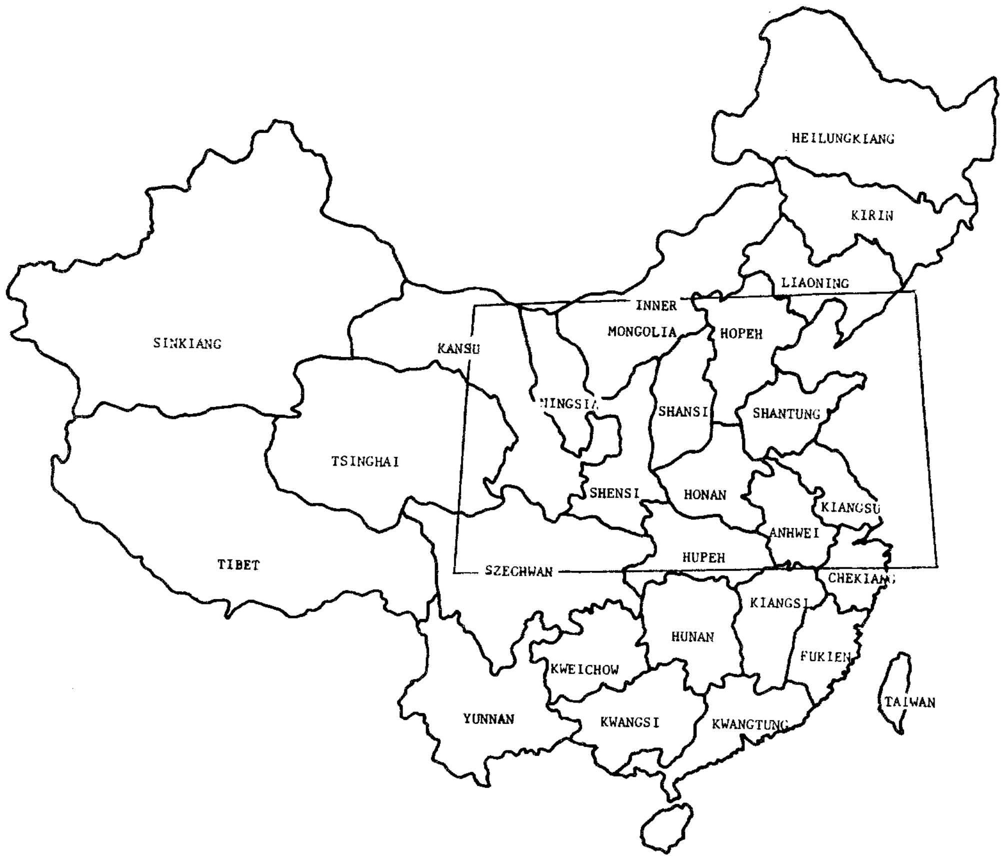

Figure 6
Provinces of China. The boxed area is defined in the text as 'Central China'.

complete even in 'Central China'. Despite a history of some 3000 years, more and more earthquakes are absent from our present catalog as we go back in time.

Corrections to the earthquake catalog in 'Central China'

A list of earthquakes in 'Central China' was extracted from the earthquake catalogs given by LEE, WU, and JACOBSEN (1976) and LEE, WU, and WANG (1978), and is given in Table 2. A breakdown of the number of earthquakes by century is presented in Table 3, and it is evident that there are considerable variations. As discussed in the previous sections, there are many factors leading to fewer and fewer earthquakes in an earthquake catalog as one goes back in time. We shall now make an effort to correct for these factors.

One major factor is the 'stability' of the dynasties. If there were wars and famines,

Table 2

List of earthquakes in 'Central China'

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
1	-1177				34.5 N	107.8 E		4.5	SHENSI
2	-780				34.5 N	107.8 E ?		6.5	SHENSI
3	-231				36.5 N	111.5 E		6.5	SHANSI
4	-193	FEB			35.4 N	103.9 E		6.5	KANSU
5	-186	FEB	22		33.4 N	104.8 E		6.5	KANSU
6	-159	JUN			32.2 N	110.4 E		5.	HUPEH
7	-154				32.2 N	110.4 E		5.	HUPEH
8	-142?				32.2 N	110.4 E		5.	HUPEH
9	- 70	JUN	1		36.3 N	119.0 E		7.0	SHANTUNG
10	- 47	APR	17		35.1 N	104.6 E		6.75	KANSU
11	- 35	JUL			34.4 N	109.0 E		5.	SHENSI
12	46	OCT	23		33.0 N	112.5 E		6.5	HONAN
13	128	FEB	23		34.7 N	105.4 E		6.5	KANSU
14	138	MAR	1		35.5 N	104.0 E		6.75	KANSU
15	143	OCT			34.7 N	105.3 E ?		7.0	KANSU
16	294	JUL			32.6 N	116.8 E		5.5	ANHWEI
17	294	SEP			40.3 N	116.0 E		5.5	HOPEH
18	319	JUN	17		34.0 N	105.2 E		4.5	KANSU
19	344				36.3 N	114.5 E		5.5	HOPEH
20	373	AUG			36.6 N	101.8 E		4.75	TSINGHAI
21	406	JUN			36.3 N	104.5 E		5.5	KANSU
22	408				36.8 N	118.3 E		5.	SHANTUNG
23	408				39.0 N	100.5 E		4.75	KANSU
24	416				34.3 N	105.5 E		5.	KANSU
25	421				41.6 N	120.4 E		5.	LIAONING
26	462	AUG	16		35.6 N	116.8 E		5.5	SHANTUNG
27	495	MAR	31		37.5 N	121.2 E		5.5	SHANTUNG
28	506	AUG	30		37.9 N	102.6 E		4.75	KANSU
29	512	MAY	21		39.0 N	113.0 E		7.5	SHANSI
30	575	JAN	14		37.9 N	102.6 E		5.5	KANSU
31	600	DEC	13		34.3 N	108.9 E		5.5	SHENSI
32	638	FEB	11		32.6 N	103.6 E		5.	SZECHWAN
33	649	SEP	12		36.1 N	111.5 E		5.5	SHANSI
34	692	MAR?			37.5 N	117.5 E		5.	SHANTUNG
35	734	MAR	19		34.7 N	106.3 E		7.0	KANSU
36	756	NOV	27		39.0 N	100.5 E		6.0	KANSU
37	777				37.8 N	115.2 E		6.0	HOPEH
38	788	MAR	8		32.5 N	109.2 E		6.5	SHENSI
39	793	MAY	27		34.5 N	109.7 E ?		6.0	SHENSI
40	835	APR	11		34.3 N	108.9 E		4.75	SHENSI
41	836	FEB	25		34.3 N	108.9 E		4.75	SHENSI
42	839				34.4 N	104.0 E		6.5	KANSU
43	865	DEC			35.9 N	111.4 E		5.5	SHANSI
44	867	FEB	14		35.9 N	111.4 E		5.5	SHANSI
45	876	JUL	14		37.8 N	105.9 E		6.5	NINGSIA

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
46	879	MAR			34.2 N	109.3 E		4.75	SHENSI
47	880	FEB			34.5 N	107.8 E		4.75	SHENSI
48	953	NOV			36.3 N	115.1 E		4.75	HOPEH
49	999	OCT			31.8 N	119.9 E		5.5	KIANGSU
50	1010	NOV			38.1 N	106.4 E		5.5	NINGSIA
51	1011	AUG			38.2 N	114.6 E		4.75	HOPEH
52	1022	APR			39.7 N	113.1 E		6.5	SHANSI
53	1038	JAN	9		38.4 N	112.9 E		7.25	SHANSI
54	1046	APR	18		37.8 N	120.7 E		5.	SHANTUNG
55	1057				39.5 N	116.3 E ?		6.75	HOPEH
56	1068	AUG	14		38.5 N	116.1 E		6.0	HOPEH
57	1069	JAN	18		38.3 N	116.8 E		4.75	HOPEH
58	1076	DEC			39.9 N	116.4 E		5.	HOPEH
59	1092	DEC?			37.9 N	102.6 E		4.75	KANSU
60	1125	AUG	30		36.0 N	103.9 E		7.0	KANSU
61	1143	APR			38.5 N	106.3 E		6.5	NINGSIA
62	1169	JAN	24		31.9 N	104.4 E		4.75	SZECHWAN
63	1209	DEC	04		36.0 N	111.8 E		6.5	SHANSI
64	1219	MAY	21		36.0 N	106.2 E		6.5	NINGSIA
65	1290	SEP	27		41.5 N	119.3 E		6.75	LIAONING
66	1291	AUG	25		36.1 N	111.5 E		6.5	SHANSI
67	1303	SEP	17		36.3 N	111.7 E		8.0	SHANSI
68	1304	FEB			36.1 N	111.5 E		5.5	SHANSI
69	1304	SEP	3		37.5 N	112.6 E		4.75	SHANSI
70	1305	MAY	3		39.8 N	113.1 E		6.5	SHANSI
71	1306	SEP	12		35.9 N	106.1 E		6.5	NINGSIA
72	1314	OCT	5		36.5 N	113.8 E		6.0	HOPEH
73	1316				36.4 N	111.1 E		5.5	SHANSI
74	1322				40.6 N	115.0 E		4.5	HOPEH
75	1336	MAR?			30.1 N	115.9 E		4.7	HUPEH
76	1337	SEP	8		40.4 N	115.7 E ?		6.5	HOPEH
77	1338	AUG	2		40.4 N	115.2 E		5.	HOPEH
78	1342	MAY	5		37.9 N	112.6 E		5.5	SHANSI
79	1346	APR			37.1 N	118.0 E		4.75	SHANTUNG
80	1351	MAY	14		37.3 N	113.0 E ?		5.5	SHANSI
81	1352	APR	18		35.6 N	105.3 E ?		7.0	KANSU
82	1368	JUL	8		37.6 N	112.5 E		6.0	SHANSI
83	1372	AUG	16		32.0 N	118.8 E		4.75	KIANGSU
84	1378	APR	30		38.5 N	106.3 E		5.75	NINGSIA
85	1399	APR	29		32.0 N	118.8 E		4.75	KIANGSU
86	1407	NOV			31.2 N	112.6 E		5.5	HUPEH
87	1425	MAR	7		31.7 N	116.5 E		5.75	ANHWEI
88	1433				30.5 N	115.2 E		4.75	HUPEH
89	1440	OCT	26		36.2 N	103.4 E		6.25	KANSU
90	1448	SEP	30		38.3 N	109.7 E		5.	SHENSI

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
91	1467	JUN	9		39.6 N	112.3 E		5.5	SHANSI
92	1469	NOV	4		31.2 N	112.6 E		5.	HUPEH
93	1474	DEC	11		38.0 N	106.3 E		5.5	NINGSIA
94	1477	MAR	19		35.2 N	104.2 E		5.	KANSU
95	1477	MAY	13		38.5 N	106.3 E		6.5	NINGSIA
96	1484	JAN	29		40.4 N	116.1 E		6.75	HOPEH
97	1485	JAN	17		34.8 N	110.4 E		5.	SHANSI
98	1485	MAY	27		40.2 N	118.0 E		5.	HOPEH
99	1487	AUG	10		34.3 N	109.1 E		6.25	SHENSI
100	1488	SEP	15		31.7 N	103.9 E		5.5	SZECHWAN
101	1495	APR	10		37.6 N	105.6 E		6.25	NINGSIA
102	1497	FEB	17		36.3 N	112.9 E		4.75	SHANSI
103	1501	JAN	19		34.8 N	110.1 E		7.	SHENSI
104	1502	JAN	17		34.8 N	110.1 E		5.	SHENSI
105	1502	OCT	17		35.7 N	115.3 E		6.5	HONAN
106	1505	JUL	10		37.8 N	105.9 E		5.5	NINGSIA
107	1505	OCT	16		35.3 N	110.8 E		5.	SHANSI
108	1506	MAR	19		35.3 N	110.1 E		5.5	SHENSI
109	1506	AUG	28		36.3 N	120.7 E		4.75	SHANTUNG
110	1522	JAN	28		34.2 N	114.1 E		5.75	HONAN
111	1523	AUG	14		30.0 N	122.1 E		5.5	CHEKIANG
112	1524	FEB	4		33.8 N	113.9 E		5.75	HONAN
113	1527				39.8 N	118.1 E		5.5	HOPEH
114	1528	JUN?			37.9 N	114.7 E		5.	HOPEH
115	1532	NOV	6		39.9 N	116.9 E		5.5	HOPEH
116	1536	OCT	22		39.8 N	116.8 E		6.	HOPEH
117	1537	MAY	13		33.6 N	117.6 E		5.5	ANHWEI
118	1538				38.0 N	115.6 E		5.	HOPEH
119	1542				39.0 N	111.0 E		5.	SHANSI
120	1542	NOV	19		34.7 N	104.9 E		5.	KANSU
121	1548	SEP	13		37.8 N	120.7 E		6.	SHANTUNG
122	1549	JUN			37.0 N	111.9 E		5.	SHANSI
123	1556	JAN	23		34.5 N	109.7 E		8.	SHENSI
124	1556	DEC	3		38.8 N	101.1 E		5.	KANSU
125	1558	JUN			37.5 N	112.2 E		5.	SHANSI
126	1558	NOV	21		34.5 N	109.7 E		5.5	SHENSI
127	1561	FEB	21		38.8 N	101.1 E		5.	KANSU
128	1561	JUL	25		37.4 N	106.0 E		7.25	NINGSIA
129	1562				38.5 N	106.3 E		5.	NINGSIA
130	1562	JUN			39.7 N	118.7 E		5.	HOPEH
131	1567				39.7 N	119.2 E		4.75	HOPEH
132	1568	JAN	.		34.2 N	109.3 E		5.	SHENSI
133	1568	APR	1		38.5 N	106.3 E		5.75	NINGSIA
134	1568	APR	2		34.4 N	109.2 E		5.5	SHENSI
135	1568	APR	12		33.1 N	107.0 E		5.	SHENSI

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
136	1568	APR	25		39.0 N	119.0 E		6.	HOPEH
137	1568	MAY	15		34.4 N	109.0 E		6.75	SHENSI
138	1569				32.7 N	109.0 E		5.	SHENSI
139	1569				34.6 N	110.3 E		5.	SHENSI
140	1573	JAN	10		34.4 N	104.0 E		6.75	KANSU
141	1578	JUL	17		40.4 N	115.7 E		5.	HOPEH
142	1580	SEP	5		39.5 N	112.3 E		5.5	SHANSI
143	1581	MAY	18		39.8 N	114.5 E		6.	HOPEH
144	1581	JUL			33.0 N	104.6 E		5.5	KANSU
145	1582	MAR			40.1 N	113.2 E		5.	SHANSI
146	1583	MAY	18		39.7 N	113.8 E ?		5.5	SHANSI
147	1584	MAR	6		30.8 N	115.7 E		5.5	HUPEH
148	1584	APR			38.4 N	111.9 E		4.75	SHANSI
149	1585	MAR	6		31.2 N	117.7 E		6.	ANHWEI
150	1586	MAY	26		39.9 N	116.3 E		5.	HOPEH
151	1587	APR	10		35.3 N	113.5 E		6.	HONAN
152	1587	OCT	4		35.2 N	110.8 E		5.	SHANSI
153	1588	AUG			38.4 N	112.8 E		5.	SHANSI
154	1590	JUL			36.5 N	102.7 E		5.	TSINGHAI
155	1590	JUL	7		35.4 N	103.9 E		5.5	KANSU
156	1591				36.6 N	110.2 E		5.	SHENSI
157	1591	NOV	21		38.8 N	101.1 E		5.	KANSU
158	1597	FEB	14		31.9 N	104.3 E		5.	SZECHWAN
159	1599				35.6 N	109.2 E		5.	SHENSI
160	1603	MAY	30		31.2 N	112.6 E		5.	HUPEH
161	1604	OCT	25		34.2 N	105.0 E		6.	KANSU
162	1608	SEP	23		37.5 N	105.7 E		5.5	NINGSIA
163	1610	MAR	9		32.5 N	104.5 E		5.5	SZECHWAN
164	1614	OCT	23		37.2 N	112.5 E		6.	SHANSI
165	1615	MAR	1		32.0 N	120.9 E		5.	KIANGSU
166	1615	JUL	20		38.8 N	106.3 E		5.5	NINGSIA
167	1616	FEB	10		37.8 N	105.9 E		5.75	NINGSIA
168	1616	OCT	10		40.9 N	116.0 E		5.	HOPEH
169	1618	MAY	20		37.0 N	111.9 E		6.5	SHANSI
170	1618	NOV	16		39.8 N	114.5 E		6.	HOPEH
171	1620	OCT	19		37.1 N	117.5 E		4.75	SHANTUNG
172	1621	MAR			39.4 N	116.8 E		5.5	HOPEH
173	1621	MAY			39.1 N	110.9 E		5.	SHENSI
174	1621	DEC?			31.0 N	120.7 E		5.	KIANGSU
175	1622	MAR	18		35.5 N	116.0 E		6.	SHANTUNG
176	1622	APR	17		36.6 N	116.8 E ?		5.5	SHANTUNG
177	1622	SEP			34.7 N	107.7 E		5.	SHENSI
178	1622	OCT	25		36.5 N	106.3 E		7.	NINGSIA
179	1623	DEC	26		36.0 N	115.1 E		4.75	HONAN
180	1624	FEB	10		32.5 N	119.5 E		6.	KIANGSU

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
181	1624	MAR?			38.4 N	112.8 E		5.	SHANSI
182	1624	APR	17		39.7 N	118.7 E		6.25	HOPEH
183	1624	JUL	4		35.4 N	105.9 E		6.	KANSU
184	1624	JUL	19		38.8 N	115.5 E		5.5	HOPEH
185	1624	SEP	1		31.1 N	121.4 E		5.	KIANGSU
186	1624	SEP			33.2 N	107.5 E		5.5	SHENSI
187	1625	APR			38.3 N	116.8 E		5.	HOPEH
188	1626	JUN	28		39.4 N	114.2 E		7.	SHANSI
189	1627	FEB	16		37.5 N	105.5 E		6.	NINGSIA
190	1627	JUN?			37.6 N	113.7 E		5.5	SHANSI
191	1628	DEC?			33.0 N	104.6 E		5.5	KANSU
192	1629	MAR			36.0 N	103.9 E		5.	KANSU
193	1630				30.7 N	113.5 E		5.	HUPEH
194	1630	JAN	16		32.6 N	104.1 E		6.25	SZECHWAN
195	1630	OCT	14		30.4 N	113.5 E		5.	HUPEH
196	1631				33.7 N	106.2 E		5.	KANSU
197	1631	JUL	21		35.3 N	104.3 E		5.	KANSU
198	1631	JUL			35.5 N	107.8 E		5.	KANSU
199	1633				32.4 N	109.7 E		5.	HUPEH
200	1633				37.3 N	111.8 E		5.	SHANSI
201	1634	JAN			34.0 N	105.2 E		6.	KANSU
202	1634	MAR			30.7 N	115.1 E		5.5	HUPEH
203	1634	DEC			35.1 N	107.7 E		5.5	KANSU
204	1635	OCT	26		33.2 N	107.5 E		5.5	SHENSI
205	1636				33.1 N	107.0 E		5.5	SHENSI
206	1636				37.0 N	108.9 E		4.75	SHENSI
207	1638	JAN			36.6 N	105.7 E		5.5	NINGSIA
208	1640	APR			34.7 N	112.5 E		5.	HONAN
209	1640	SEP			30.4 N	114.9 E		5.	HUPEH
210	1641	JUN	21		34.3 N	105.5 E		4.75	KANSU
211	1642				33.0 N	118.4 E		5.	KIANGSU
212	1642	JUN	30		34.9 N	111.1 E		6.	SHANSI
213	1652	FEB	10		31.4 N	116.3 E		5.	ANHWEI
214	1652	MAR	23		31.5 N	116.5 E		6.	ANHWEI
215	1652	AUG			33.4 N	104.8 E		5.5	KANSU
216	1653				33.1 N	107.0 E		5.	SHENSI
217	1654	JUL	21		34.3 N	105.5 E		7.5	KANSU
218	1654	SEP	15		36.1 N	115.6 E		5.5	SHANTUNG
219	1657	APR	21		31.5 N	103.7 E		6.0	SZECHWAN
220	1658	FEB	3		39.4 N	115.7 E		6.	HOPEH
221	1662				33.4 N	120.1 E		4.75	KIANGSU
222	1662	OCT	11		33.2 N	114.8 E		5.5	HONAN
223	1664				38.7 N	112.7 E		5.5	SHANSI
224	1664	APR	1		39.9 N	116.7 E		4.75	HOPEH
225	1665				37.9 N	102.6 E		5.	KANSU

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
226	1665	APR	16		39.9 N	116.7 E		6.5	HOPEH
227	1668	JUL	25		35.3 N	118.6 E		8.5	SHANTUNG
228	1671	SEP			35.3 N	118.0 E		5.	SHANTUNG
229	1673	MAR	29		31.8 N	117.3 E		5.	ANHWEI
230	1673	OCT	18		40.5 N	114.1 E		5.5	SHANSI
231	1673	OCT	18		39.0 N	111.0 E		5.5	SHANSI
232	1675				34.1 N	114.8 E		5.5	HONAN
233	1675	JUN			34.8 N	111.1 E		4.75	SHANSI
234	1675	JUN			35.6 N	115.9 E		5.	SHANTUNG
235	1677	SEP			33.4 N	104.8 E		5.5	KANSU
236	1678	JUN?			40.7 N	115.3 E		5.	HOPEH
237	1679	SEP	2		40.0 N	117.0 E		8.	HOPEH
238	1679	OCT			37.5 N	112.5 E		5.5	SHANSI
239	1683	NOV	22		38.7 N	112.7 E		7.	SHANSI
240	1686				37.1 N	106.4 E		5.	NINGSIA
241	1695	MAY	18		36.0 N	111.5 E		8.	SHANSI
242	1698				41.5 N	121.2 E		5.	LIAONING
243	1704	SEP	18		38.0 N	116.5 E		5.5	HOPEH
244	1704	SEP	28		34.9 N	106.8 E		6.	SHENSI
245	1708	OCT	26		36.7 N	114.7 E		5.5	HOPEH
246	1709	OCT	14		37.4 N	105.3 E		7.5	NINGSIA
247	1713	SEP	4		32.0 N	103.7 E		6.5	SZECHWAN
248	1718	JUN	19		35.0 N	105.2 E		7.5	KANSU
249	1720	JUL	12		40.4 N	115.5 E		6.75	HOPEH
250	1724				40.4 N	115.2 E		5.	HOPEH
251	1725	JUL			30.0 N	102.0 E		5.5	SZECHWAN
252	1730	SEP	30		40.0 N	116.2 E		6.5	HOPEH
253	1730	DEC?			36.9 N	117.9 E		5.	SHANTUNG
254	1731	NOV			31.4 N	121.0 E		5.	KIANGSU
255	1734	MAR			30.3 N	103.5 E		5.	SZECHWAN
256	1737	SEP	30		35.3 N	113.8 E		5.5	HONAN
257	1738	MAY	19		33.2 N	104.2 E		5.5	SZECHWAN
258	1739	JAN	3		38.9 N	106.5 E		8.	NINGSIA
259	1739	FEB	13		38.5 N	106.3 E		5.5	NINGSIA
260	1742				32.0 N	110.8 E		5.	HUPEH
261	1743	JUN	29		30.7 N	118.4 E		5.5	ANHWEI
262	1746	JUL	29		40.2 N	116.2 E		5.	HOPEH
263	1748	FEB	23		31.3 N	103.4 E		5.5	SZECHWAN
264	1748	AUG	29		30.5 N	101.5 E		5.5	SZECHWAN
265	1748	NOV	21		36.4 N	106.1 E		5.5	NINGSIA
266	1754	MAY			37.7 N	112.5 E		5.	SHANSI
267	1765	MAR	15		41.8 N	123.4 E		5.5	LIAONING
268	1765	MAY	1		35.3 N	103.9 E		5.25	KANSU
269	1765	SEP	2		34.8 N	105.0 E		6.5	KANSU
270	1772	MAR	1		38.3 N	114.4 E		5.	HOPEH

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
271	1785	DEC?			30.5 N	101.5 E		5.	SZECHWAN
272	1787	DEC	13		31.0 N	103.7 E		4.75	SZECHWAN
273	1789	NOV	7		34.6 N	110.3 E		5.	SHENSI
274	1791	FEB	11		38.0 N	115.5 E		5.	HOPEH
275	1792	SEP	7		30.5 N	101.5 E		6.	SZECHWAN
276	1792	NOV	30		30.5 N	101.5 E		5.5	SZECHWAN
277	1793	MAY	15		30.5 N	101.5 E		6.	SZECHWAN
278	1795	AUG	5		39.7 N	118.7 E		5.25	HOPEH
279	1796	MAR			36.0 N	119.4 E		5.	SHANTUNG
280	1805	JUN	25		37.1 N	114.5 E		5.	HOPEH
281	1805	AUG	5		39.7 N	119.2 E		5.5	HOPEH
282	1811	SEP	27		31.7 N	100.3 E		6.	SZECHWAN
283	1812	APR	2		34.6 N	110.6 E		5.	HONAN
284	1813				36.0 N	111.4 E		5.25	SHANSI
285	1814	FEB	4		35.8 N	114.4 E		5.25	HONAN
286	1815	AUG	6		39.0 N	117.5 E		5.	HOPEH
287	1815	OCT	23		34.8 N	111.2 E		6.75	SHANSI
288	1819	FEB	24		36.3 N	102.3 E		5.75	TSINGHAI
289	1820	AUG	3		34.1 N	113.9 E		6.	HONAN
290	1820	OCT			34.8 N	111.2 E		5.	HONAN
291	1822	JUN	18		33.0 N	104.6 E		5.5	KANSU
292	1823	AUG			32.5 N	107.9 E		5.	SHENSI
293	1827	MAR	23		34.9 N	111.1 E		5.25	SHANSI
294	1829	APR			37.5 N	111.2 E		5.25	SHANSI
295	1829	AUG	18		34.6 N	110.6 E		5.	HONAN
296	1829	NOV	18		33.2 N	117.9 E		5.5	ANHWEI
297	1829	NOV	19		36.6 N	118.5 E		6.	SHANTUNG
298	1830	JUN	12		36.4 N	114.2 E		7.5	HOPEH
299	1831				35.9 N	117.8 E		5.	SHANTUNG
300	1831	SEP	28		32.8 N	116.9 E		6.25	ANHWEI
301	1835	JUN	6		36.3 N	116.4 E		5.	SHANTUNG
302	1837	SEP	15?		34.6 N	103.7 E		6.	KANSU
303	1846				31.6 N	106.0 E		5.5	SZECHWAN
304	1847	MAR			34.8 N	111.8 E		5.	HONAN
305	1850				34.7 N	104.9 E		5.	KANSU
306	1852	MAY	26		37.5 N	105.2 E		6.	NINGSIA
307	1855	FEB	27		30.1 N	120.0 E		5.	CHEKIANG
308	1855	DEC	11		39.1 N	121.7 E		5.5	LIAONING
309	1856	APR	10		39.1 N	121.7 E		5.25	LIAONING
310	1859	SEP	19		40.7 N	122.2 E		5.	LIAONING
311	1861	JUL	19		39.1 N	121.7 E		6.	LIAONING
312	1862	DEC	23		35.5 N	111.5 E		5.5	SHANSI
313	1867	SEP			30.5 N	120.8 E		5.	CHEKIANG
314	1868	OCT	30		32.4 N	117.8 E		5.5	ANHWEI
315	1879	MAY	12		31.8 N	104.8 E		5.	SZECHWAN

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
316	1879	JUL	1		33.2 N	104.7 E		7.5	KANSU
317	1880	SEP	30		39.7 N	118.7 E		5.	HOPEH
318	1881	JUL	20		33.6 N	104.6 E		6.5	KANSU
319	1882	DEC	2		38.1 N	115.5 E		6.	HOPEH
320	1885	JAN	14		34.5 N	105.7 E		6.	KANSU
321	1885	FEB	21		40.7 N	122.2 E		5.	LIAONING
322	1887	JUL			37.0 N	103.8 E		5.	KANSU
323	1888	JUN	13		38.5 N	119.0 E		7.5	SHANTUNG
324	1888	NOV	2		37.1 N	104.2 E		6.25	KANSU
325	1889	SEP			38.1 N	106.3 E		5.	NINGSIA
326	1889	OCT			36.3 N	115.1 E		5.	HOPEH
327	1890				36.9 N	112.9 E		5.5	SHANSI
328	1890	FEB	17		36.6 N	101.8 E		5.	TSINGHAI
329	1891	APR	17		37.0 N	111.9 E		5.75	SHANSI
330	1893	FEB	23		38.3 N	116.8 E		5.	HOPEH
331	1893	JUN	1		36.6 N	101.8 E		5.5	TSINGHAI
332	1893	AUG	29		30.5 N	101.5 E		6.	SZECHWAN
333	1898	SEP	22		39.1 N	113.0 E		5.5	SHANSI
334	1904	AUG	30		31.2 N	100.9 E		6.	SZECHWAN
335	1910	JAN	8	14:49:30.0	35.0 N	122.0 E		6.75	HUANGHAI*
336	1917	JAN	24	0:48:12.0	31.3 N	116.3 E		6.25	ANHWEI
337	1919	MAY	29	10:59:45.0	31.5 N	100.5 E		6.25	SZECHWAN
338	1919	AUG	25	19:55:15.0	32.0 N	100.0 E		6.25	SZECHWAN
339	1920	DEC	16	12: 5:53.0	36.5 N	105.7 E		8.5	NINGSIA
340	1920	DEC	25	11:33: 8.0	35.6 N	106.3 E		7.	NINGSIA
341	1920	DEC	28	3:16:30.0	35.5 N	105.5 E		6.25	KANSU
342	1921	JAN	6	23: 9:45.0	38.0 N	107.0 E		6.	NINGSIA
343	1921	JAN	7	9:42:25.0	38.0 N	107.0 E		6.	NINGSIA
344	1921	APR	12	9:36: 0.0	35.8 N	106.2 E		6.5	NINGSIA
345	1923	MAR	24	12:40: 6.0	31.3 N	100.8 E		7.3	SZECHWAN
346	1927	FEB	3	3:53:10.0	33.5 N	121.0 E		6.5	HUANGHAI*
347	1927	MAY	22	22:32:47.0	37.6 N	102.6 E	25	8.0	KANSU
348	1927	MAY	23	13:51:10.0	37.7 N	102.2 E		6.	KANSU
349	1928	MAR	7	22:43:28.0	37.6 N	102.2 E		6.	KANSU
350	1929	JAN	13	18:44:39.0	40.7 N	111.3 E		6.	INNER M.
351	1932	MAR	6	21:43:50.0	30.1 N	101.8 E		6.	SZECHWAN
352	1932	APR	6	9:11:18.0	31.4 N	115.0 E		6.	HUPEH
353	1932	AUG	22	11:12:42.0	36.1 N	121.6 E		6.25	HUANGHAI*
354	1933	AUG	25	7:50:30.0	32.0 N	103.7 E		7.4	SZECHWAN
355	1934	JAN	20	17:56:16.0	41.1 N	108.3 E		6.25	INNER M.
356	1935	JUL	26	10:32:31.0	33.3 N	101.1 E		6.	TSINGHAI
357	1936	FEB	7	8:56:27.0	35.4 N	103.4 E		6.75	KANSU
358	1936	AUG	1	6:24:30.0	34.2 N	105.7 E		6.	KANSU
359	1937	JUL	31	20:35:48.0	35.2 N	115.3 E		6.9	SHANTUNG
360	1937	AUG	1	10:41: 5.0	35.3 N	115.4 E		6.75	SHANTUNG

Table 2 (*continued*)

NO	YEAR	MO	DY	HR:MN: SEC	LAT	LONG	DEPTH	MAG	REGION
361	1938	MAR	14	5:14:21.0	32.3 N	103.6 E		6.	SZECHWAN
362	1941	JUN	11	23:13:31.0	30.1 N	102.5 E		6.	SZECHWAN
363	1941	OCT	8	15:24:20.0	32.1 N	103.3 E		6.	SZECHWAN
364	1944	DEC	19	14: 9: 4.0	39.7 N	124.3 E		6.75	LIAONING*
365	1945	SEP	23	15:34:23.0	39.7 N	118.7 E		6.25	HOPEH
366	1948	MAY	23	9:13:18.0	37.7 N	121.9 E		6.	SHANTUNG*
367	1949	JUN	15	9:42:42.0	33.3 N	100.0 E		6.	TSINGHAI
368	1952	OCT	31	23:51:40.0	33.3 N	101.0 E		6.	TSINGHAI
369	1954	FEB	11	0:30:15.0	39.0 N	101.3 E		7.25	KANSU
370	1954	FEB	11	4:53:46.0	39.0 N	101.5 E		6.	KANSU
371	1954	JUL	31	1: 0: 0.0	38.8 N	104.2 E		7.	KANSU
372	1955	APR	14	1:29: 2.0	30.0 N	101.8 E		7.5	SZECHWAN
373	1955	OCT	1	6:29:54.0	30.0 N	101.4 E		6.	SZECHWAN
374	1958	FEB	7	23:23:36.0	31.5 N	104.0 E		6.2	SZECHWAN
375	1960	NOV	9	10:43:42.0	32.78N	103.67E		6.75	SZECHWAN
376	1966	MAR	7	21:29:14.0	37.35N	114.92E	10	6.8	HOPEH
377	1966	MAR	22	8:11:36.0	37.50N	115.08E		6.7	HOPEH
378	1966	MAR	22	8:19:46.0	37.53N	115.05E		7.2	HOPEH
379	1966	MAR	26	15:19: 4.0	37.60N	115.27E	15	6.2	HOPEH
380	1966	MAR	29	6:11:59.0	37.47N	114.88E	25	6.	HOPEH
381	1967	MAR	27	8:58:20.0	38.5 N	116.5 E	30	6.3	HOPEH
382	1967	AUG	30	4:22: 9.0	31.62N	100.33E	8	6.8	SZECHWAN
383	1967	AUG	30	11: 8:51.0	31.70N	100.33E		6.	SZECHWAN
384	1969	JUL	18	5:24:49.0	38.2 N	119.4 E	35	7.4	PO HAI *
385	1970	FEB	24	2: 7:34.4	30.65N	103.28E	15	6.2	SZECHWAN
386	1973	FEB	6	10:37: 8.3	31.3 N	100.9 E	17	7.9	SZECHWAN
387	1973	FEB	7	16: 6:27.0	31.5 N	100.3 E	8	6.0	SZECHWAN
388	1973	AUG	11	7:15:34.6	32.88N	104.00E	8	6.5	SZECHWAN
389	1975	FEB	4	11:36: 6.0	40.65N	122.80E	12	7.3	LIAONING
390	1976	APR	5	16:54:40.1	40.2 N	112.2 E		6.2	INNER M.
391	1976	JUL	27	19:42:54.6	39.4 N	118.1 E		7.8	HOPEH
392	1976	JUL	27	23:17:31.4	39.2 N	117.9 E		6.2	HOPEH
393	1976	JUL	28	10:45:35.2	39.7 N	118.7 E		7.0	HOPEH
394	1976	AUG	16	14: 6:45.9	32.9 N	104.1 E		7.1	SZECHWAN
395	1976	AUG	21	21:49:54.2	32.7 N	104.2 E		6.6	SZECHWAN
396	1976	AUG	23	3:30: 7.6	32.5 N	104.1 E		6.6	SZECHWAN
397	1976	SEP	22	20: 7: 3.2	40.1 N	106.4 E		6.	INNER M.
398	1976	NOV	15	13:53: 0.6	39.4 N	117.9 E		6.5	HOPEH

Table 3

Number of earthquakes in 'Central China' with corrections

Century	Number of earthquakes	Probability	Corrected number of earthquakes
1	1	0.05	21
2	3	0.06	54
3	2	0.05	41
4	3	0.05	56
5	7	0.06	118
6	3	0.07	44
7	4	0.08	50
8	5	0.08	64
9	8	0.07	111
10	2	0.08	26
11	10	0.18	56
12	3	0.37	8
13	4	0.55	7
14	19	0.73	26
15	17	0.91	19
16	57	1.00	57
17	83	0.87	100
18	37	0.96	39
19	54	1.00	54
20	(86)*)	1.00	(86)

*) There are actually 65 earthquakes from 1900–76, so we extrapolate it to 100 years.

the chance for an earthquake to be recorded and the information to be preserved would decrease. A measure of the dynasty stability is the census data which were collected for taxation. The taxation census is probably not a true measure of the actual population, but rather reflects how well the dynasty is in control of the country. Detailed taxation census appeared in dynasty records, and a summary may be found in CHANG (1959). A plot of the census data is given in Fig. 7. It is rather surprising that the taxation census show an apparent population of about 30 million from 0 to A.D. 1700 with large fluctuations. The apparent population increased more than 10-fold in the 18th century for reasons that scholars are still debating.

There are four major 'troughs' in Fig. 7 which are related to wars and major dynasty changes. The first decrease is related to the change from the Former Han dynasty to the Later Han dynasty. The second decrease is related to the breaking up of China into several warring factions at the end of the Later Han dynasty. The third decrease occurred during the middle of the Tang dynasty when there were extensive influxes of western tribes into 'Central China'. The fourth decrease is due to the change from the Ming dynasty to the Ching dynasty when the Manchu tribe from northeastern China crossed the Great Wall and took over 'Central China'.

It is not clear to us how to best utilize the taxation census to correct for earthquakes that were not recorded. We use a simple model here for our initial investigation.

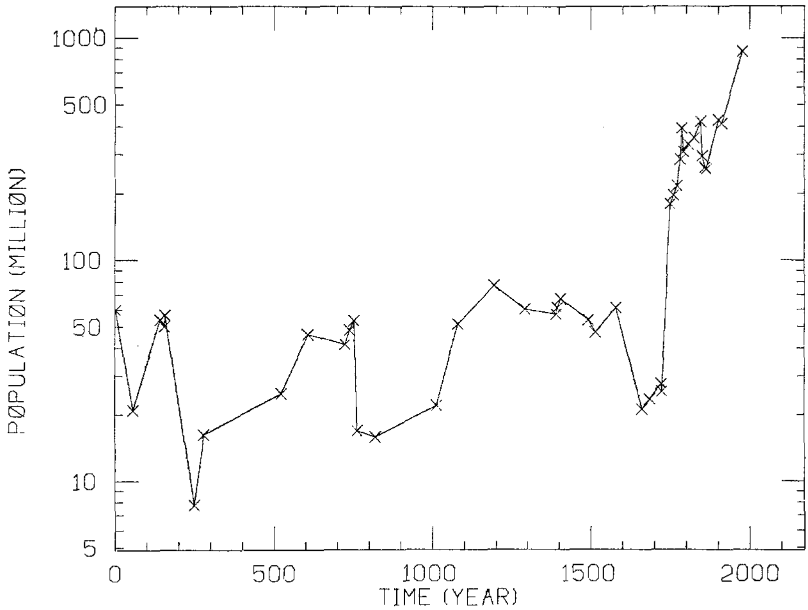

Figure 7
Apparent population in China according to taxation census.

The probability, Π_1, that an earthquake will be recorded at time t is modelled by:

$$\Pi_1(t) = 1 - C[(S - P(t))/S]; \qquad \Pi_1(t) \leq 1$$

where $P(t)$ is the apparent population according to taxation census, S is a saturation population, and C is a constant. Both S and C are model constants, and we choose $S = 50$ million and $C = 1/3$. Obviously $\Pi_1(t)$ cannot be greater than 1 and we impose this condition. The resulting probability as a function of time is given in Fig. 8.

Another major factor is how well the historical earthquake records are preserved in the present literature. It is obvious that printing plays an important part in preserving historical records, and the advent of printing occurred in the 10th century and became widespread by the 15th century. Therefore, we may construct a simple model for the probability, Π_2, that an earthquake record is preserved by specifying:

$$\begin{aligned} \Pi_2(t) &= C_1 \quad \text{at} \quad t = \text{A.D. } 0 \\ &= C_2 \quad \text{at} \quad t = \text{A.D. } 1000 \\ &= 1 \quad \text{at} \quad t = \text{A.D. } 1500 \end{aligned}$$

where C_1 and C_2 are constants, and Π_2 linearly extrapolated between values at given times. The resulting probability is given by Fig. 9 for $C_1 = 0.05$ and $C_2 = 0.1$. (These constants were chosen arbitrarily.)

We may combine the above two probabilities (Π_1 and Π_2) into a probability (Π) that an earthquake will appear in present literature. Specifically,

$$\Pi(t) = \Pi_1(t)\Pi_2(t).$$

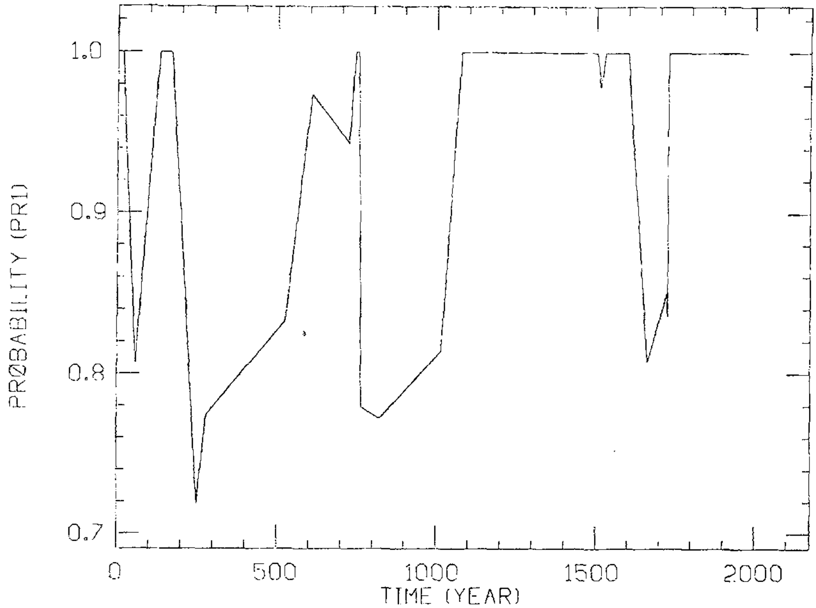

Figure 8
Probability function according to apparent population.

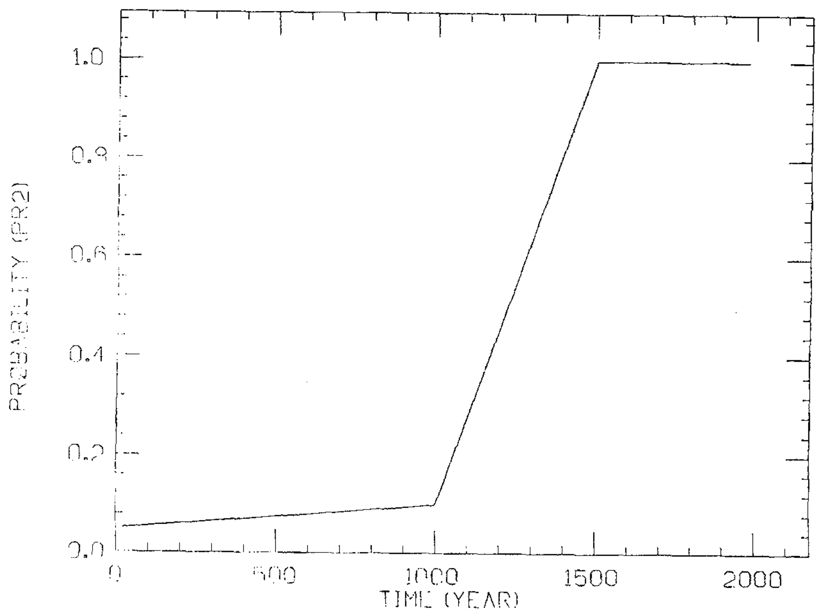

Figure 9
Probability function of document survival which we assumed for our data analysis.

The resulting probability function is shown in Fig. 10. By dividing the observed number of earthquakes by this probability we may estimate the number of earthquakes in each century and the results are shown in Table 3 and Figure 11. Because there are very few earthquakes in our catalog before A.D. 1000, corrections by the probability function tend to introduce large fluctuations and are unreliable. Corrections to data after A.D. 1000 seem to bring out a relatively high seismicity in the 11th and 14th centuries more clearly. This simple exercise supports the well-known argument that there is a temporal pattern of seismicity in China (SHI *et al.*, 1978). Earthquake activity perhaps increases at an interval of about 300 years as evidenced by the relatively large numbers of earthquakes in the 11th, 14th, 17th, and 20th centuries in comparison to their adjacent centuries.

Another way to count the number of earthquakes is through a moving time window. This method has the advantage of representing the data more realistically as a function of time. We shall restrict ourselves to the data from A.D. 1000 to the present. If we count the number of earthquakes in a time window of 50 years at increments of 20 years, we have the curve as shown in Fig. 12. If we use the probability function (Fig. 10) to correct the earthquake data as described above, we have the curve as shown in Fig. 13. The results are suggestive that seismicity peaked at the 11th, 14th, 17th and perhaps the 20th century.

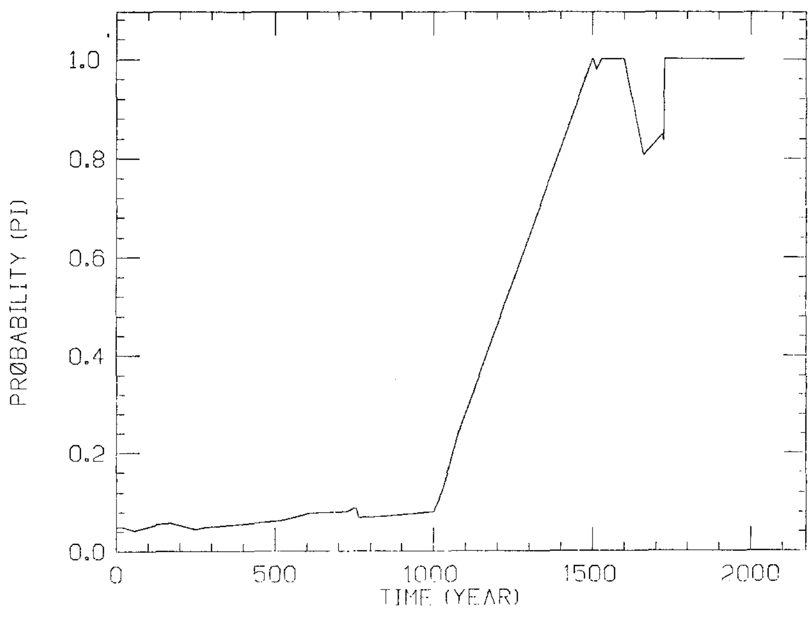

Figure 10
Probability function that an earthquake occurring in time *t* will appear in our catalog. See text for our assumptions.

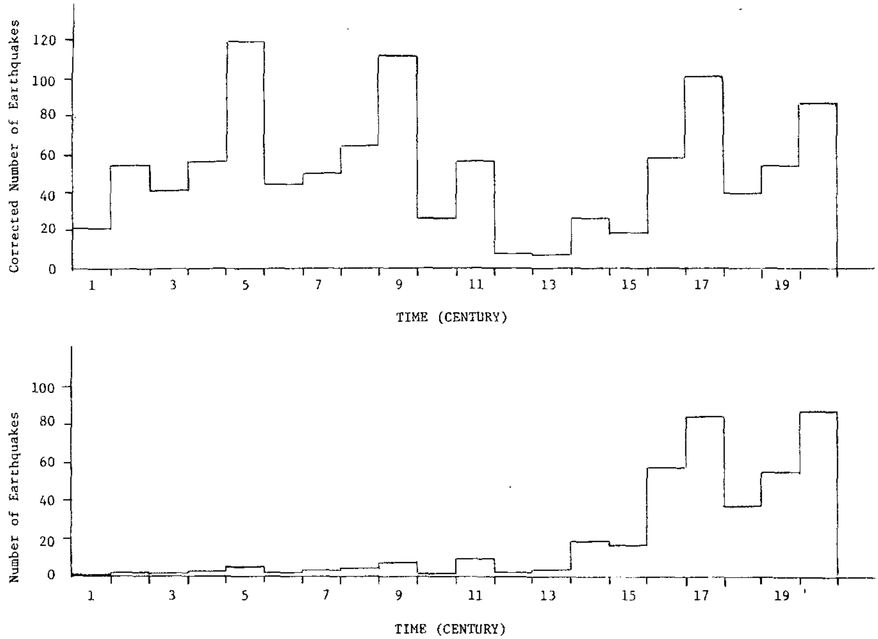

Figure 11
Number and corrected number of earthquakes per century in 'Central China'.

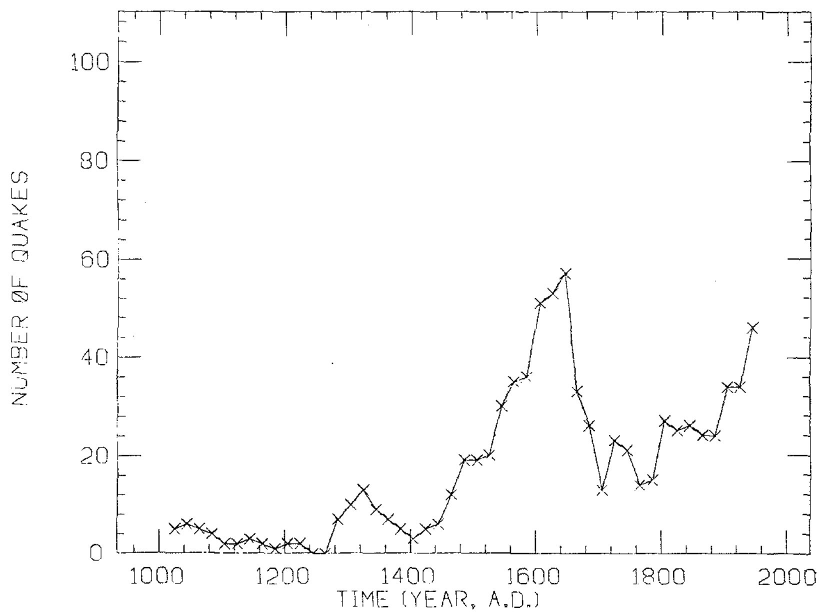

Figure 12
Number of earthquakes in 'Central China' in a moving window of 50 years.

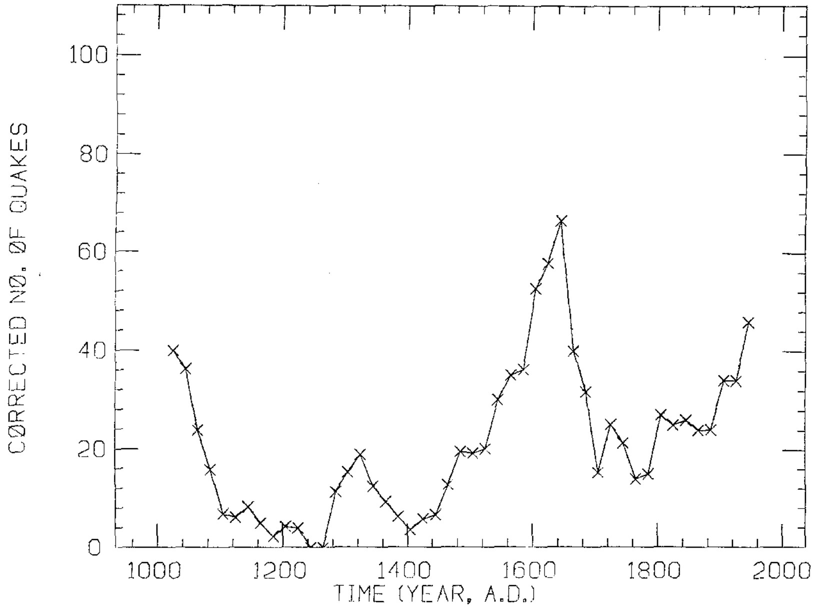

Figure 13
Corrected number of earthquakes in 'Central China' in a moving window of 50 years.

Point process analysis

In recent years, point process analysis has been introduced into statistics to analyze a sequence of times of events in manners similar to those of ordinary time series analysis. General introductions to point process analysis may be found in Cox and LEWIS (1966), DALEY and VERE-JONES (1972) and BRILLINGER (1976). Applications of the theory to seismology may be found in VERE-JONES (1970), LOMNITZ (1974), UDIAS and RICE (1975), KAGAN and KNOPOFF (1976, 1978).

By a point process we mean a sequence of times, say $\tau_1, \tau_2, \tau_3, \ldots$, at which certain events of interest occur. By a stochastic point process we mean a point process in which the times at which the events occur is random. A stochastic point process may be characterized by giving the probability distribution of the number of events in particular time intervals or collections of intervals. It may alternately be characterized by giving the probability distribution of the times between successive events. In the seismological case the events are earthquakes and the times are those at which certain earthquakes of interest occurred.

A point process is often described by a counting function $N(t)$, with $N(t)$ giving the number of events in the time interval $(0, t]$. This is a nondecreasing step function that increases by 1 every time a new event occurs. Using the Dirac delta function one may give a symbolic representation of the derivative of the point process as

$$\frac{dN(t)}{dt} = \sum_j \delta(t - \tau_j)$$

where the τ_j are the times of the events. In a variety of circumstances this derivative may be viewed as an ordinary time series and suggestive expressions set down. This series will be 0 for almost all t, but infinite at times at which events occur.

A key descriptor of a stochastic point process is provided by its rate, or intensity, function. This is defined as

$$h_N(t) = \lim_{h \downarrow 0} \text{Prob}\,\{\text{event in the time interval } (t, t + h)\}/h$$

and is analogous to the mean function of an ordinary (stochastic) time series. An important second-order parameter is provided by the autointensity function

$$h_{NN}(t_1, t_2) = \lim_{h \downarrow 0} \text{Prob}\,\{\text{event in } (t_1, t_1 + h) | \text{event at } t_2\}/h \qquad t_1 \neq t_2,$$

measuring the degree of serial dependence of the process in a certain sense.

A stochastic point process is called stationary if its probabilistic properties are unaffected by shift of the time origin. In this situation the rate function is constant and the (above) autointensity function depends on $t_1 - t_2$ alone. In our application of point process analysis to the Chinese earthquake data, a basic assumption is that the earthquake-generating process is not changing in time, and that the earthquakes generated correspond to a realization of a stationary stochastic point process. This seems reasonable in view of the theory of plate tectonics suggesting that the plate motions which generate earthquakes do not change in a time span of a few thousand years.

Let $\tau_1, \tau_2, \tau_3, \ldots$ denote the times of the earthquakes occurring in our earthquake catalog and let $N(t)$ denote the corresponding counting function. We further assume that the probability of an earthquake occurring at time t being listed in our catalog is $\Pi(t)$ and that the events being listed are statistically independent for each event. (We recognize that this is not totally realistic as whole stretches of events may have been lost or unrecorded together, but it seems a reasonable first approximation.) For simplicity in this initial study we shall take the function of Fig. 10 for $\Pi(t)$. The derivative of the process $N(t)$ now has the representations

$$\frac{dN(t)}{dt} = \sum_j \delta(t - \tau_j) = \sum_k I_k(t - \sigma_k)$$

with the I_k independent 0–1 variates having

$$\text{Prob}\,\{I_k = 1\} = \Pi(\sigma_k)$$

$$\text{Prob}\,\{I_k = 0\} = 1 - \Pi(\sigma_k)$$

where the σ_k are the times at which earthquakes actually occurred. Let the point process $M(t)$, of actual earthquake times, have rate h_M and autointensity function $h_{MM}(t)$, then the rate of the process $N(t)$ is

$$h_N(t) = \Pi(t)h_M$$

and its autointensity is

$$h_{NN}(t_1, t_2) = \Pi(t)h_{MM}(t_1 - t_2).$$

Estimates of the rate and autointensity function of a stationary point process are discussed in Cox and Lewis (1966) and Brillinger (1976). (Examples are given in Udias and Rice [1975].)

Supposing the catalog covers the time interval (0, T] with $N(T)$ events occurring in total at times $\tau_1, \tau_2, \ldots, \tau_{N(T)}$, the rate of the basic process M may be estimated by

$$\hat{h}_M = T^{-1} \sum_{j=1}^{N(T)} 1/\Pi(\tau_j).$$

Further, the autointensity of the M process may be estimated by

$$\hat{h}_{MM}(t) = \frac{1}{\beta T \hat{h}_M} \sum_{i \neq j} \{|\tau_i - \tau_j - t| < \beta/2\}/[\Pi(\tau_i)\Pi(\tau_j)]$$

with the symbol $\{E\}$ defined to be 1 if the event E is true and to be 0 if E is false and with β, a cell width. (In fact in our calculations the above estimate $\hat{h}_{MM}(t)$ is weighted together with $\hat{h}_M$ in order that the estimate has the proper behavior for large t.)

We have estimated the autointensity function for the earthquake sequence in our catalog from A.D. 1000 to A.D. 1976. The result is shown in Fig. 14 where the first peak

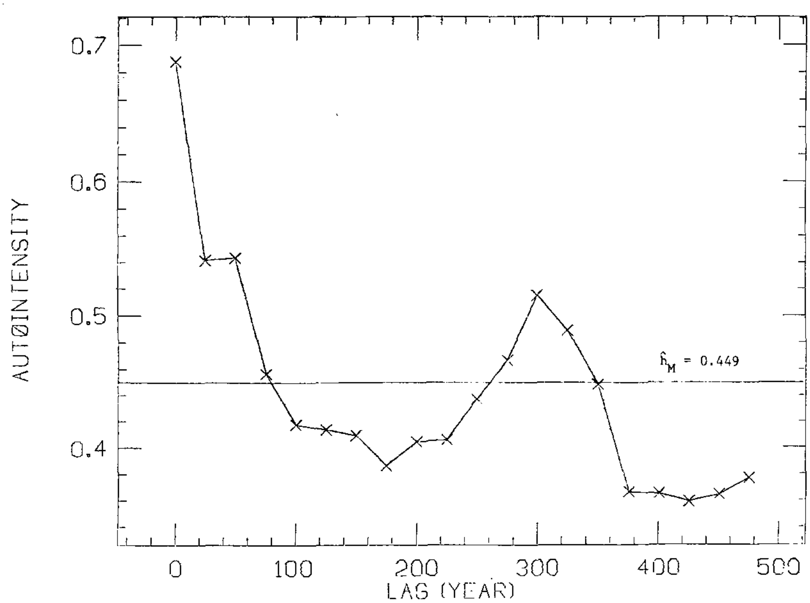

Figure 14
Autointensity function for the earthquake sequence in 'Central China' from A.D. 1000 to A.D. 1976. See text for explanations.

of the curve suggests a periodicity of about 300 years in the occurrence of earthquakes in 'Central China'. The result is in agreement with the earlier findings described in the previous section. The central peak suggests the clustering together of the events partly due to aftershocks. For our present data ($T = 977$ years, $N(t) = 349$), we obtain the rate of earthquake occurrence, $\hat{h}_M$, equal to 0.449 events/year from the formula given. This corresponds to about 45 events per century.

The variance of $\hat{h}_{MM}(t)$ may be estimated by

$$\sigma^2 = \Big(\beta T\hat{h}_M\hat{h}_{MM}(t) + 4\sum_{i<j} W_{ij}(1 - \Pi_i\Pi_j)\Big/\Pi_i^2\Pi_j^2 + 8\sum_{i<j<k} W_{ij}W_{ik}(1 - \Pi_i)\Big/\Pi_i^2\Pi_j\Pi_k + 8\sum_{i<j<k} W_{ij}W_{jk}(1 - \Pi_j)\Big/\Pi_i\Pi_j^2\Pi_k + 8\sum_{i<j<k} W_{ik}W_{jk}(1 - \Pi_k)\Big/\Pi_i\Pi_j\Pi_k^2\Big)\Big/(\beta T\hat{h}_M)^2$$

where $\Pi_i = \Pi(\tau_i)$, and $W_{ij} = \{|\tau_i - \tau_j - t| < \beta/2\}$. This formula is derived in BRILLINGER (1979). Its derivation neglects the variation in the estimated Πs. This seems reasonable here. The case of $\Pi(t) = 1$ is considered in BRILLINGER (1976).

Table 4 gives the values of $\hat{h}_{MM}(t)$ and its estimated standard error for the case of $\beta = 25$ years. The fourth column of the table provides a measure of the deviation of

Table 4

Estimated standard error of the sample autointensity function

Lag (year)	$\hat{h}_{MM}(t)$	Standard error, ε	$(\hat{h}_{MM}(t) - \hat{h}_M)/\varepsilon$
0	0.688	0.117	8.07
25	0.541	0.083	1.09
50	0.543	0.059	1.46
75	0.457	0.036	0.19
100	0.418	0.021	−1.62
125	0.414	0.027	−1.36
150	0.409	0.023	−1.63
175	0.386	0.020	−3.20
200	0.404	0.025	−1.86
225	0.406	0.025	−1.70
250	0.437	0.030	−0.48
275	0.467	0.042	0.40
300	0.515	0.047	1.35
325	0.489	0.040	1.04
350	0.448	0.026	0.05
375	0.366	0.018	−4.64
400	0.365	0.023	−3.50
425	0.359	0.030	−2.91
450	0.365	0.034	−2.40
475	0.377	0.045	−1.55

the estimated autointensity function from that of a purely random distribution of events. There are clear suggestions of significant deviations. The principal ones being a clustering of events in the bin of lags from 0 to 12.5 years (due to aftershocks and tectonic coupling of main shocks), and suggestions of low seismicity at lags near 175 years and near 375 years. A further deviation is one of increased seismicity at about 300 years. Please note that the clustering of earthquakes to a lag of 12.5 years is influenced by our choice of bin width of 25 years. In other words, the extent of clustering in time may actually be less than 12.5 years.

Discussion

It is obvious that the results from analyses of historical earthquakes depend critically on the quality and completeness of the earthquake catalog. In 'Central China', the present catalog is inadequate before A.D. 1500 and we are now in the process of improving the existing catalog and developing methods of dealing with its incompleteness. We also plan to develop an extensive set of statistical tools to analyze the data, and would welcome suggestions and comments.

Acknowledgments

We wish to thank M. G. Bonilla, T. Hanks, and M. Wyss for comments on the manuscript.

References

Academia Sinica, Seismological Committee (1956), *Chronological Tables of Earthquake Data of China*, Science Press, Peking, 2 vols., 1653 pp. (in Chinese).

Academia Sinica, Institute of Geophysics (1970a), *Catalog of Chinese Earthquakes*, Academia Sinica, Peking, 361 pp. (in Chinese).

Academia Sinica, Institute of Geophysics (1970b), *Summary of Large Earthquakes in China* (from 780 B.C. to February 1970, with magnitude ≥ 6), Academia Sinica, Peking, 29 pp. (in Chinese).

Academia Sinica, Institute of Geophysics (1974), *Summary of Large Earthquakes in China* (from 780 B.C. to 1973, with magnitude ≥ 6). Academia Sinica, Peking, 31 pp. (in Chinese).

Academia Sinica, Institute of Geophysics (1976), *Summary of Large Earthquakes in China* (from 780 B.C. to 1976, with magnitude ≥ 6), Academia Sinica, Peking, 29 pp. (in Chinese).

Brillinger, D. R. (1976), *Measuring the association of point processes: a case history*, Am. Math. Monthly *83*, 16–22.

Brillinger, D. R. (1979), *Analyzing point processes subjected to random deletions*, Can. J. Statistics, in press.

Chang, C. Y. (1959), *China's Population Problem*, Chinese Population Society, Taipei, 444 pp. (in Chinese).

Cox, D. R., and Lewis, P. A. W. (1966), *The Statistical Analysis of Series of Events*, Barnes & Noble, New York.

DALEY, D. J., and VERE-JONES, D. (1972), *A summary of the theory of point processes, in 'Stochastic Point Processes'*, edited by P. A. W. Lewis, Wiley-Interscience, New York, pp. 299–383.

DRAKE, N. F. (1912), *Destructive earthquakes in China*, Bull. Seism. Soc. Am. *2*, 45–91.

FESSLER, L. (1963), *China*, Time Inc., New York, 176 pp.

HSIEH, C. M. (1973), *Atlas of China*, McGraw-Hill, New York, 282 pp.

HSIEH, Y. S. (1957), *A new scale of seismic intensity adapted to the conditions in Chinese territories*, Acta Geophys. Sinica *6*, 35–47 (in Chinese with English abstract).

KAGAN, Y. and KNOPOFF, L. (1976), *Statistical search for non-random features of the seismicity of strong earthquakes*, Phys. Earth Planetary Interiors *12*, 291–318.

KAGAN, Y. and KNOPOFF, L. (1978). *Statistical study of the occurrence of shallow earthquakes*, Publ. 1694, Inst. Geophys. Planetary Physic., UCLA.

LEE, S. P. (1958). *A practical magnitude scale*, Acta Geophys. Sinica *7*, 98–102 (in Chinese with English abstract).

LEE, W. H. K., WU, F. T. and JACOBSEN, C. (1976), *A catalog of historical earthquakes in China compiled from recent Chinese publications*, Bull. Seism. Soc. Am. *66*, 2003–2016.

LEE, W. H. K, WU, F. T. and WANG, S. C. (1978), *A catalog of instrumentally determined earthquakes in China (Magnitude ≥6) compiled from various sources*, Bull. Seism. Soc. Am. *68*, 383–398.

LOMNITZ, C. (1974), *Global Tectonics and Earthquake Risk*, Elsevier, Amsterdam.

SHI, C. L., HUAN, W. L. ZHAO, X. L. WU, H. Y. LIU, Y. B. and HUANG, W. G. (1978), *Some characteristics of seismic activity in China*, Chinese Geophys. *1*, 231–244. (English translation of *Acta Geophys. Sinica 17*, 1–13, 1974.)

UDIAS, A. and RICE, J. (1975), *Statistical analysis of microearthquake activity near San Andreas Geophysical Observatory, Hollister, California*, Bull. Seism. Soc. Am. *65*, 809–827.

VERE-JONES, D. (1970), *Stochastic models for earthquake occurrence*, J. R. Stat. Soc. B. *32*, 1–62.

(Received 15th September 1978)